



Energetic valorization of wood waste: Estimation of the reduction in CO₂ emissions

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ABSTRACT

This paper investigates the potential CO₂ emission reductions related to a partial switch from fossil fuel-based heat and electricity generation to renewable wood waste-based systems in Flanders. The results show that valorization in large-scale CHP (combined heat and power) systems and co-firing in coal plants have the largest CO₂ reduction per TJ wood waste. However, at current co-firing rates of 10%, the CO₂ reduction per GWh of electricity that can be achieved by co-firing in coal plants is five times lower than the CO₂ reduction per GWh of large-scale CHP. Moreover, analysis of the effect of government support for co-firing of wood waste in coal-fired power plants on the marginal costs of electricity generation plants reveals that the effect of the European Emission Trading Scheme (EU ETS) is effectively counterbalanced. This is due to the fact that biomass integrated gasification combined cycles (BIGCC) are not yet commercially available. An increase of the fraction of coal-based electricity in the total electricity generation from 8 to 10% at the expense of the fraction of gas-based electricity due to the government support for co-firing wood waste, would compensate entirely for the CO₂ reduction by substitution of coal by wood waste. This clearly illustrates the possibility of a 'rebound' effect on the CO₂ reduction due to government support for co-combustion of wood waste in an electricity generation system with large installed capacity of coal- and gas-based power plants, such as the Belgian one.

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1. Introduction

Worldwide targets are set to cut the anthropogenic greenhouse gas (GHG) emissions in order to limit global warming. In early 2008 the European Commission unveiled an integrated energy and climate package (EUROPEAN COMMISSION, 2008). The coming years will be challenging, given the variety and complexity of energy and climate targets established. The National Energy Efficiency Action Plans aim for 9% savings by 2016 (EUROPEAN COMMISSION, 2006) while the new emission trading scheme (ETS) directive (EUROPEAN COMMISSION, 2009b) along with other climate policy instruments are aimed at a 20% GHG reduction by 2020 (relative to 1990). Another important instrument in the abatement of GHG is the new Renewables Directive (EUROPEAN COMMISSION, 2009a). The EU target is to achieve a share of 20% renewable energy in 2020 (compared to a share of 7.8% in 2007 (Eurostat, 2009)). To achieve this EU target national targets were set according to the renewable energy potential of each country. Belgium is committed to increase its share of renewable energy to 13% by 2020 (EUROPEAN COMMISSION, 2009a). To promote renewable energy a 'green certificate' system for electricity produced from renew-

able resources has been established in the Flemish Region (Flemish government, 2004).

Bioenergy is the largest renewable energy contributor to global primary energy today and has the highest potential of all renewable energy sources (INTERNATIONAL ENERGY AGENCY, 2008). Within this bioenergy category wood plays an important role worldwide. In residential heating systems wood is used as boards or pellets in stoves. In underdeveloped countries wood is still the major fuel for cooking purposes. For electricity generation wood is used either in centralized coal-fired power plants (co-combustion of wood dust or wood pellets) or in decentralized combined heat and power (CHP) Stirling engines or steam turbines. In Flanders more than 30% of the renewable electricity generation of 1641 GWh in 2007 was based on wood (Public Waste Agency of Flanders (OVAM), 2009). To generate this electricity 531,178 tons of wood was energetically valorized (Public Waste Agency of Flanders (OVAM), 2009). This wood consisted for 56% of uncontaminated¹ wood waste of which 173,728 tons originated from local woodworking industries and 123,711 tons consisted of post-consumer waste (Public Waste Agency of Flanders (OVAM), 2009). The remaining 44% consisted of imported wood pellets. The exact origin of these wood pellets is not known and the potential for large-scale short rotation forestry is very small in a

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¹ Uncontaminated wood waste is all wood waste that has not been treated with preservatives containing heavy metals or halogenated organic compounds.

densely populated region as Flanders (Vande Walle et al., 2007). Therefore only energetic valorization of locally generated uncontaminated wood waste will be discussed in this paper. Co-combustion in coal-fired electricity plants was the main energy conversion option as 62.0% of the wood waste was valorized in that way. The remaining wood waste was valorized in large-scale CHP (23.5%) and was used for heating of greenhouses (14.5%).

There are several studies analyzing the CO₂ reduction when wood is used instead of fossil fuels in large scale power plants or small scale heating systems. Different studies show that the use of wood for electricity generation results in environmental benefits in comparison with coal-based systems (Benetto et al., 2004; Hartmann and Kaltschmitt, 1999; Skodras et al., 2004; Spath and Mann, 2004). These environmental profits include reduction in CO₂ emissions. Hektor (1998) found that the CO₂ emission of a wood-based heating system was much lower compared to different fossil fuel reference systems. Raymer (2006) came to the same conclusion and also found that there is not much difference in the CO₂ reduction for different kinds of wood. The study of Wahlund et al. (2004) appears to be the most complete in comparing the CO₂ reduction of different options for energetic valorization of woody biomass. Two main options for electricity generation were examined (Faaij, 2006): co-combustion of coal and wood on the one hand, and gasification of wood followed by combustion of the syngas in a gas turbine cycle combined with a steam cycle, a so-called biomass integrated gasification combined cycle (BIGCC) on the other hand. Different options for refining wood to motor fuels, such as methanol and ethanol were considered. Also the CO₂ reduction of two different CHP systems was presented. The only option that was not considered is the use of wood in small-scale heating systems.

In the study presented in this paper the CO₂ reduction through the use of wood waste instead of fossil fuels is calculated for 4 different options for electricity generation: co-combustion in coal-fired power plant, co-combustion of syngas in gas-fired power plant (BIGCC), dedicated wood combustion power plant and combustion in municipal solid waste incinerator (MSWI). Also two CHP systems are considered: a small-scale system for domestic use and a large-scale system for industrial applications. Furthermore, the CO₂ reduction of three different small-scale heating systems is calculated: an open fireplace, a wood stove and a central heating system with wood-fired boiler. The different options for wood refining to motor fuels are not examined as the potential application in Flanders is very small due to the limited amount of resources. Besides, Wahlund et al. (2004) and Gustavsson et al. (1995) showed that these options have generally a much lower CO₂ reduction than electricity generation or CHP. The authors are aware of the current discussions with respect to other emissions (other than CO₂) caused by the energetic valorization of wood waste. However, due to a lack of comparable emission data of other greenhouse gases and non-GHG pollutants, and to facilitate comparison with the study of Wahlund et al. (2004), it was decided to focus the discussion on CO₂ emissions.

The CO₂ reduction will be calculated taking into account specific data and boundary conditions for the Flemish Region (Northern part of Belgium). A major issue in the calculation of the CO₂ reduction is the choice of the reference system based on fossil fuels or, equivalently, which fossil fuel is replaced and which emissions are thus avoided (Schlamadinger et al., 1997). Not all studies give a clear argumentation of the choice of the reference plant for electricity generation. It seems evident that in the case of co-combustion of wood and coal, coal-based electricity is substituted. However, the marginal cost of electricity production will be impacted significantly by co-firing wood waste. If the marginal cost is reduced by co-firing, the average load level of the power plant could be increased, assuming the plants were not yet working at full capacity, thereby substituting for example gas-based electricity in another plant. Therefore, it is absolutely necessary to take into account the characteristics of the

electricity generation system of the country or region under study. Wahlund et al. (2004) correctly addressed the reference problem by choosing a reference which constitutes the marginal production in the Swedish electricity generation system. In Sweden, where 90% of the generated electricity is either nuclear power or hydropower (Eurostat, 2009), coal-based electricity plants were at the time of the study the most expensive electricity plants. All additional generated electricity therefore substituted coal-based electricity. For Belgium, where 55% of the generated electricity comes from nuclear power, 30% comes from gas-based plants and 8% comes from coal-based plants, the situation could be different (Eurostat, 2009).

In the first part of this paper the marginal electricity production will be identified for the Belgian electricity generation system. This will enable in the second and third parts of the paper to calculate the CO₂ reduction per GJ wood waste and per GWh electricity, respectively, by using an adequate reference system. In the fourth part of the paper particular attention will be addressed to the effect on the CO₂ reduction of a possible shift from gas- to coal-based electricity generation. This shift could be the result of government support for co-combustion of wood waste and significantly reduce the CO₂ reduction achieved in practice. This paper is to our knowledge the first to recognize the possibility of a 'rebound' effect on the CO₂ reduction due to government support for co-combustion of wood waste in an electricity generation system with large installed capacity of coal- and gas-fired plants.

2. Methodology and assumptions

2.1. Characteristics energy conversion plants

All parameters used for the calculation of the CO₂ reduction are summarized in Table 1. The range on the efficiencies reflects as much as possible the actual spread in Flanders. Large-scale gasification of wood waste and subsequent co-combustion of the syngas in natural gas combined cycle plants (BIGCC) are not yet commercially available. For this option the average reported efficiency, as found in the literature, is used. Using average efficiencies will yield more realistic predictions of the CO₂ reduction than using the highest reported efficiency. For BIGCC Wahlund et al. (2004) used an efficiency of 45% which corresponds to the maximum value reported in the literature. Also for CHP systems the difference between the nominal efficiency and the operational efficiency can be significant (Evald and Witt, 2006). An electrical efficiency of 30% and a total fuel utilization ratio of 90% or even 115% with fuel gas condensation, as assumed by Wahlund et al. (2004), is hardly achieved in practice (Evald and Witt, 2006). A lot of CHP systems seem to suffer in practice from decreased thermal efficiency due to full load operation in combination with low heat demand or decreased electrical efficiency due to partial load operation in combination with low heat demand. The main origin for the decreased operational efficiency is a mismatch between heat generation and heat demand due to over-sizing of the CHP system. However, economic considerations, as there is the high value of electricity produced during on-peak hours, could justify operation at lower total fuel utilization ratios (Evald and Witt, 2006). In this study a large-scale CHP is assumed to have an average electrical efficiency of 25% and a thermal efficiency of 50%. For small-scale CHP systems for domestic use the thermal over electrical power ratio is higher. For these systems an electrical efficiency of 15% and a thermal efficiency of 60% are assumed (U.S. Environmental Protection Agency (EPA) Combined Heat and Power Partnership, 2007).

2.2. Calculation of marginal costs of electricity generation

An economic optimization determines which electricity plants will decrease their load level when an additional amount of electricity is injected into the grid. The plants with the lowest marginal cost will be

Table 1Main input data for the calculation of the avoided CO₂ emissions of the different energetic valorization options.

Input	Value	Source
Lower heating value, wood (20% moisture content)	15 MJ/kg	Devriendt and Vanderstraeten (2003)
Thermal efficiency, wood in fireplace	10–20%	Van Leemput and Heuts (2007)
Thermal efficiency, wood in stove	35–90%	Van Leemput and Heuts (2007)
Thermal efficiency, wood in domestic boiler	86–94.8%	Van Leemput and Heuts (2007)
Thermal efficiency, gas in domestic boiler	70–100%	Van Leemput and Heuts (2007)
Thermal efficiency, oil in domestic boiler	70–97.5%	Van Leemput and Heuts (2007)
Thermal efficiency, coal in domestic boiler	70–89%	Van Leemput and Heuts (2007)
Thermal efficiency, resistance heating	1 MJ/MJ electricity	Organisatie voor Duurzame Energie Vlaanderen (2006)
Coefficient of performance (thermal efficiency), heat pump	2.5–6 MJ/MJ electricity	Organisatie voor Duurzame Energie Vlaanderen (2006)
Thermal efficiency, wood in small-scale CHP (<1000 kW)	60%	Evald and Witt (2006), U.S. Environmental Protection Agency (2007)
Thermal efficiency, wood in large-scale CHP	50%	Evald and Witt (2006), U.S. Environmental Protection Agency (2007)
Electrical efficiency, wood in small-scale CHP (<1000 kW)	15%	Evald and Witt (2006), U.S. Environmental Protection Agency (2007)
Electrical efficiency, wood in large-scale CHP	25%	Evald and Witt (2006), U.S. Environmental Protection Agency (2007)
Electrical efficiency, wood in waste incineration plant	20–25%	Theunis et al. (2003)
Electrical efficiency, wood in coal-fired power plant	35–38%	Devriendt and Vanderstraeten (2003)
Electrical efficiency, wood in dedicated electricity plant with steam cycle only	25–33%	Devriendt and Vanderstraeten (2003)
Electrical efficiency, wood in BIGCC	40–45%	Wahlund et al. (2004), Rodrigues et al. (2003)
Electrical efficiency, natural gas combined cycle (NGCC) power plant	50–52.5%	Devriendt and Vanderstraeten (2003)
Electrical efficiency, coal-fired power plant	37–44.2%	Devriendt and Vanderstraeten (2003)
Emission factor, gas production and transport	8.5 tons CO ₂ /TJ	Theunis et al. (2003)
Emission factor, oil production and transport	16 tons CO ₂ /TJ	Theunis et al. (2003)
Emission factor, coal production and transport	6.3 tons CO ₂ /TJ	Theunis et al. (2003)
Emission factor, wood waste transport (50 km) and pre-treatment (chipping or pelletization)	0.46–6.175 tons CO ₂ /TJ	Hoffmann et al. (2003)
Emission factor, gas combustion	50–55 tons CO ₂ /TJ	Goldthorpe (2005)
Emission factor, oil combustion	69–70 tons CO ₂ /TJ	Goldthorpe (2005)
Emission factor, coal combustion	88–93 tons CO ₂ /TJ	Goldthorpe (2005)
Emission factor, Belgian electricity generation system without nuclear power plants	180 tons CO ₂ /TJ electricity	Aernouts and Jespers (2009)

the first in the merit order of an electricity generation system and will operate continuously, irrespective of small changes in the electricity supply. In Belgium nuclear power plants provide base load electricity and it can be assumed that the load of the nuclear power plants will not be affected by the limited amount of electricity produced from wood waste (Delarue and D'Haeseleer, 2007). Only the CO₂ emissions of electricity plants with higher marginal costs, like coal- and gas-based plants, might be avoided. Oil-based peak generation units are not considered in this analysis as they provide electricity on a very irregular basis and produce only 1.6% of the total amount of electricity in Belgium (Eurostat, 2009).

The marginal cost of classical thermal plants is a function of the fuel cost and the CO₂ emission allowance cost (Delarue and D'Haeseleer, 2007), as presented by Eq. (1).

$$MC = \frac{FC}{\eta} + \frac{EC \cdot EF}{\eta} \quad (1)$$

with MC the marginal cost (€/GJ_e); FC the fuel cost (€/GJ_i); η the plant's rated efficiency (GJ_e/GJ_i); EF the CO₂ emission factor of the fuel (ton CO₂/GJ_i) and EC the CO₂ emission cost (€/ton CO₂). The revenue from sales of electricity does not appear in Eq. (1) as the revenue is assumed equal for different power plants. By comparing marginal cost functions of different power plants a switching point in the merit order can be identified for a certain parameter (Delarue and D'Haeseleer, 2007). For instance, a fuel price can be calculated above which the considered plants switch places in the merit order. If this calculated fuel price is much higher than the actual fuel price, the actual merit order can be considered stable.

Biomass-based electricity generation is supported in Flanders via a green certificate (GC) system, which is introduced to reach the targets for renewable energy in the electricity sector. For every GWh of green electricity produced a GC can be obtained. These certificates can either be traded on the GC market or in case of market failure a guaranteed minimum value can be obtained from the Flemish Gas and Electricity Regulator (VREG) (Flemish Government, 2009). The revenue from the GC system should be taken into account when calculating the marginal costs. In this analysis it is assumed that the minimum value is obtained

for the GC. For a coal-based plant with co-combustion of X% biomass on energy basis the marginal cost function is given by Eq. (2).

$$MC_{c+b} = X \cdot \left[\frac{FC_b}{\eta_b} - \frac{GCV_{\min}}{3.6} \right] + (1-X) \left[\frac{FC_c}{\eta_c} + \frac{EC \cdot EF_c}{\eta_c} \right] \quad (2)$$

with GCV_{min} the minimum value for GC. The subscripts c and b represent coal and biomass, respectively. The minimum value for GC depends on the type of generation plant. Table 2 summarizes all cost data. Table 1 summarizes all efficiencies and emission factors. The average of the efficiencies, CO₂ emission factors and costs are used for the analysis.

The electricity plant with the highest marginal cost will be the first to decrease its load and, as a result, its CO₂ emissions. The amount of CO₂ emissions that will be avoided in practice by a certain wood-based electricity generation system not only depends on the marginal cost of other electricity plants but also on technical boundary conditions like the minimum load of an electricity plant or the start-up time. If the additional amount of electricity injected into the grid is large enough, it might be necessary to decrease also the load of an electricity plant with a lower marginal cost to avoid for instance the

Table 2

Main cost data for the calculation of the marginal cost.

Input	Value	Source
Coal price	2 €/GJ	van Tilburg et al. (2007)
Natural gas price	5.7 €/GJ	van Tilburg et al. (2007)
Minimum wood price, post-consumer waste	1.4 €/GJ	van Tilburg et al. (2007)
Maximum wood price, wood pellets	6.6 €/GJ	van Tilburg et al. (2007)
CO ₂ emission allowance cost	20 €/ton CO ₂	Delarue and D'Haeseleer (2008)
Minimum value GC, co-combustion of biomass in old coal-based electricity plant	80 €/GWh	Flemish Government (2009)
Minimum value GC, co-combustion of biomass in new coal-based electricity plant	60 €/GWh	Flemish Government (2009)
Minimum value GC, biomass in new gas-based or in dedicated biomass plant or CHP	90 €/GWh	Flemish Government (2009)
Period of support after first granted GC for biomass-based electricity generation	10 years	Flemish Government (2009)

complete shutdown of a plant with a high start-up time. In order to be able to calculate the exact amount of avoided CO₂ emissions a dynamic economic optimization, taking into account all existing power plants and boundary conditions, is necessary. This, however, is beyond the scope of this study. In this study the avoided CO₂ emissions are estimated as the average of the CO₂ emissions of the electricity generation plant with the highest marginal cost and the CO₂ emissions of the Belgian electricity generation system without nuclear power.

Changes in the electricity generation system due to import of electricity or seasonal effects are neglected. Approximately 10% of the consumed electricity in Belgium is imported (Eurostat, 2009). To study long-term effects, besides marginal costs, also investment costs should be taken into consideration as new electricity plants will be built. This study is limited to short-term effects and conclusions therefore apply only to the currently installed electricity generation capacity.

2.3. Estimation of the CO₂ reduction

The primary objective of this study is to identify the valorization options with the largest CO₂ reduction. The CO₂ reduction per TJ wood waste increases with an increased efficiency of the energy conversion of wood waste and a higher CO₂ emission factor of the reference fossil fuel cycle. The CO₂ reduction per TJ wood waste decreases with an increased efficiency of the energy conversion of the fossil fuel reference and a higher CO₂ emission factor of the wood waste transport and pre-treatment. The CO₂ reduction per TJ wood waste can be calculated with Eq. (3).

$$\text{CO}_2 \text{ reduction per TJ wood waste} = \text{EF}_{\text{fossil reference}} \frac{\eta_{\text{wood waste}}}{\eta_{\text{fossil reference}}} - \text{EF}_{\text{wood waste}} \quad (3)$$

In the case of combined heat and electricity generation in a CHP installation the avoided CO₂ emissions of respectively heat and electricity generation are calculated with respect to separate heat and electricity generation using a fossil fuel reference. Finally, the avoided CO₂ emissions related to heat and electricity generation are summed. In other words for CHP Eq. (3) consists of three terms, namely the avoided CO₂ emissions of heat generation, the avoided CO₂ emissions of electricity generation and the CO₂ emission factor of wood waste transport and pre-treatment.

In Section 3.1 the most adequate fossil fuel reference will be selected for electricity generation based on the marginal costs of Belgian electricity plants. Due to the large number of different heating systems and the lack of accurate cost data, it is far more difficult to predict which type of heating system will be replaced by a wood-based heating system. Amongst the residential buildings in Flanders 47.5% are heated with natural gas, 39% with heating oil and 8.5% with electricity (Six and Dexters, 2008). The remaining 5% consists of heating systems based on coal, wood and LPG (Six and Dexters, 2008). There are however no accurate figures available for heating systems in industry. Therefore it was decided to calculate the avoided CO₂ emissions of wood-based heating for five different reference cases: a natural gas boiler, a boiler on heating oil, resistance heating, a heat pump and a boiler on coal. For heating systems based on electricity it is assumed that they consume peak power electricity and thus the average CO₂ emissions of the Belgian electricity generation system without nuclear power plants are avoided.

The CO₂ emission factors in Eq. (3) encompass all emissions from the collection of the wood waste or the extraction of the fossil fuel to the final energy conversion. The CO₂ released by combustion of wood waste is assumed to be assimilated by new biomass in a reasonable time and is thus not taken into account. The large spread on the CO₂ emission factor for wood transport and pre-treatment in Table 2

originates from the differences in the nature of the input material. The lower value of the emission factor corresponds to the emissions of transport over 50 km. This emission factor applies for sawdust as pre-treatment is generally not required for this kind of waste stream. The higher value of the emission factor corresponds to drying and pelletization followed by transport over 50 km. Sawdust as well as pellets can be used directly in each considered installation. Although some installations could handle other wood waste streams without any pre-treatment, it is generally accepted that pelletization as a pre-treatment can significantly improve the final energy conversion efficiency (Uslu et al., 2008). Therefore the emission factor of the pre-treatment is considered to depend only on the nature of the wood waste and the average CO₂ emission factor is used for all treatment options. In 2007 less than 2% of the energetically valorized wood waste originated from outside Flanders (Public Waste Agency of Flanders (OVAM), 2009). Even if the transport distance would double, the CO₂ emission factor of wood waste transport would constitute less than 1% of the emission factor of fossil fuels. As a consequence the impact of a difference in transport distance between different treatment options on the avoided CO₂ emissions can be considered small.

In Section 3.4 the effect of a shift from gas- to coal-based electricity due to co-combustion of wood waste on the average carbon intensity of the Belgian electricity generation system will be studied. Therefore the CO₂ emissions per GWh electricity should be known. For an electricity plant with X% co-combustion of wood waste on energy basis the CO₂ emissions per GWh electricity can be calculated as presented by Eq. (4).

$$\text{CO}_2 \text{ emissions per GWh electricity} = 3.6 \left(X \frac{\text{EF}_{\text{wood waste}}}{\eta_{\text{wood waste}}} + (1-X) \frac{\text{EF}_{\text{fossil reference}}}{\eta_{\text{fossil reference}}} \right) \quad (4)$$

For CHP the CO₂ emissions should be allocated to heat and electricity. Here, the direct exergetic allocation method is used. This method allocates less CO₂ emissions to electricity as the quality of the produced heat increases, as described by Eq. (5) (Mathieu et al., 1999). The quality of the heat produced is directly related to its temperature by the Carnot factor.

$$\text{CO}_2 \text{ emissions per GWh electricity} = 3.6 \left(\frac{\text{EF}_{\text{wood waste}}}{\eta_{\text{electric}} + \eta_{\text{heat}} \cdot \left(1 - \frac{T_0}{T_{\text{heat}}}\right)} \right) \quad (5)$$

The temperature of the delivered heat is assumed to be 150 °C and an ambient temperature of 20 °C is used.

Over the short-term the total amount of electricity produced from coal- and gas-based plants can be considered constant. The shift from gas- to coal-based electricity generation that would compensate entirely for the CO₂ reduction by co-firing wood waste in coal plants can then be calculated from Eq. (6).

$$x \cdot \frac{\text{EF}_{\text{coal}}}{\eta_{\text{coal}}} + (1-x) \cdot \frac{\text{EF}_{\text{gas}}}{\eta_{\text{NGCC}}} = y \cdot \frac{\text{EF}_{\text{coal}} + X\% \text{wood}}{3.6} + (1-y) \cdot \frac{\text{EF}_{\text{gas}}}{\eta_{\text{NGCC}}} \quad (6)$$

with x and y as the fraction of electricity from coal-based plants in the total of coal- and gas-based electricity generation for the situation without and with co-combustion of wood waste in coal-based plants respectively. EF_{coal + X%wood} can be calculated from Eq. (4).

3. Results and discussion

3.1. Determination of the reference for electricity generation

Fig. 1 shows that the marginal cost of natural gas plants is higher than the marginal cost of coal plants. With 13.5 €/GJ_e for natural gas

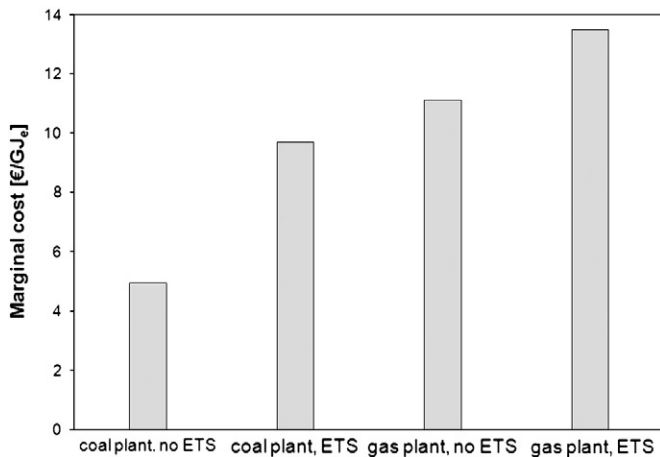


Fig. 1. The marginal cost (in €/GJ_e) of electricity plants without and with ETS (20 €/ton CO₂).

plants and 9.7 €/GJ_e for coal-fired plants the difference in marginal costs is significant. The gas price should decrease with more than 34% before coal plants become the marginal electricity production units. Similarly the CO₂ emission allowance cost should increase with a factor 2.6 to generate a switch in the merit order of coal and gas plants. It can thus be concluded that natural gas-fired plants constitute the marginal production in the Belgian electricity generation system. This means that the CO₂ emissions of natural gas-fired plants are avoided when a limited amount of electricity is injected into the grid. If the amount of electricity injected into the grid is large enough, also coal-fired plants will decrease their load and CO₂ emissions. The smaller the difference in marginal costs between coal and gas plants the higher the probability that also coal-based electricity will be substituted. This probability is significantly increased by introducing an emission trading scheme (EU ETS) with a CO₂ allowance cost of for example 20 €/ton CO₂. As a result of the CO₂ allowance cost the difference in marginal costs between coal and gas plants decreases to 3.8 €/GJ compared to 6.2 €/GJ in the absence of the EU ETS (Fig. 1).

In the case of co-combustion of wood waste in coal-fired plants the situation is different. All coal plants in Belgium that were adapted for co-combustion have approximately the same capacity as before the adaptation to co-combustion. In Section 3.2 it is therefore assumed that the average load level of the coal plant is not affected by co-combustion of wood waste. In that case wood effectively replaces coal and the CO₂ emissions of coal are avoided. The marginal cost of an electricity plant will, however, change with co-combustion of wood waste due to changes in the price of the fuel, the amount of CO₂ emission permits that have to be purchased and the amount of GC that can be obtained for electricity generation from renewable resources. The possible effect on the average load level and the avoided CO₂ emissions will be discussed in Section 3.4.

3.2. CO₂ reduction per TJ of wood waste

Fig. 2 shows that the difference in CO₂ reduction between different valorization options is generally much smaller than the difference in CO₂ reduction between different references for heat generation for the same valorization option. The difference between the five references for heat generation is so large that it is even impossible to identify an energetic valorization option that has the highest CO₂ emission reduction irrespective of the reference for heat generation. Therefore it is necessary to discuss the results for each reference system separately.

If heating oil is chosen as a reference fuel for heat generation, then a wood-fired boiler has the largest CO₂ reduction with 89 tons CO₂/TJ. Large-scale CHP is the runner-up with a CO₂ reduction of 85 tons CO₂/TJ. This result seems remarkable as CHP is generally considered as the

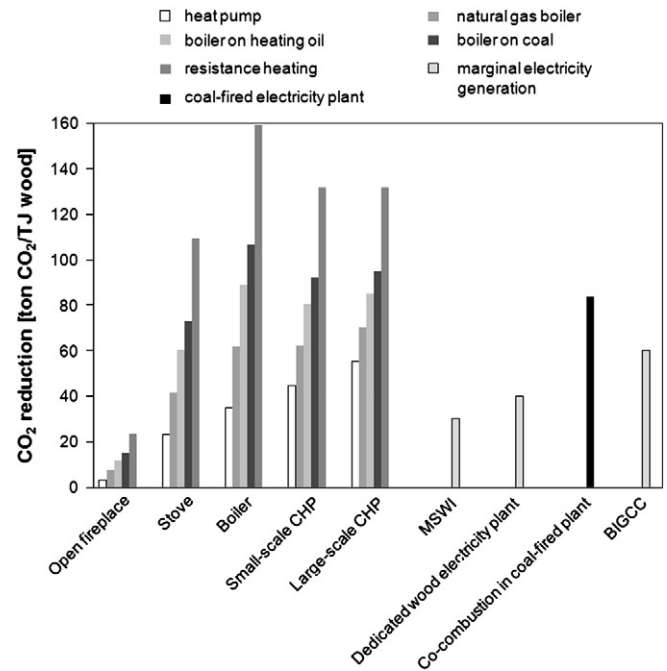


Fig. 2. CO₂ reduction (in ton CO₂/TJ wood) of different energy conversion options for wood waste, using five different references of heat generation (heat pump, natural gas boiler, boiler on heating oil, boiler on coal, resistance heating), using the marginal electricity generation plant as reference for electricity generation, except in the case of co-combustion in a coal-fired plant, where the coal-fired electricity plant is used as reference.

technology with the highest theoretical efficiency. If we consider a CHP system with an electrical efficiency of 30% and a thermal efficiency of 60% like Wahlund et al. (2004) did, CHP is with 103 tons CO₂/TJ the technology with the highest CO₂ reduction. However, operational CHP efficiencies, which have been used here, can be significantly lower than the theoretical efficiencies (Evald and Witt, 2006). Moreover, in the Belgian electricity generation system gas-based electricity plants constitute the marginal electricity production. As the CO₂ emission factor of natural gas is much smaller than the CO₂ emission factor of heating oil, more CO₂ emissions can be avoided by replacing oil-based heat generation than by replacing gas-based electricity generation. Co-combustion in coal-based plants has a CO₂ reduction of 84 tons CO₂/TJ and application in small-scale CHP has a CO₂ reduction of 80 tons CO₂/TJ. Due to uncertainties in the operational efficiencies the four energetic valorization options of wood waste, namely a boiler, coal plant, small- or large-scale CHP, can be considered equivalent from the point of view of CO₂ reduction with an oil-based heating system as a reference. Valorization in BIGCC with a CO₂ reduction of 60 tons CO₂/TJ is clearly less interesting and is equivalent with valorization in a stove, which has a CO₂ reduction of 61 tons CO₂/TJ. Although BIGCC is the technique with the highest electrical efficiency, the fact that gas-based electricity generation will be avoided makes it a less interesting option. It is clear that a dedicated wood combustion plant with steam cycle is even worse with a CO₂ reduction of 40 tons CO₂/TJ. The options with the lowest CO₂ reduction are valorization in a MSWI and an open fireplace with a CO₂ reduction of 30 and 12 tons CO₂/TJ, respectively.

If natural gas is chosen as a reference fuel for heat generation then co-combustion in a coal-fired plant has with 84 tons CO₂/TJ clearly the largest CO₂ reduction. Large-scale CHP is again the runner-up with a CO₂ reduction of 70 tons CO₂/TJ. Small-scale CHP and a wood-fired boiler both have a CO₂ reduction of 62 tons CO₂/TJ, which is equivalent with the CO₂ reduction of BIGCC. Valorization in a stove is with a CO₂ reduction of 42 tons CO₂/TJ equivalent with a dedicated wood

combustion plant. Valorization in a MSWI and an open fireplace remain the options with the lowest CO₂ reduction.

Natural gas and heating oil are the most important fuels for heat generation in Flanders, especially for domestic heating, as discussed in Section 2.3. Electricity-based heating systems, such as heat pumps and to a lesser extent resistance heating, have consistently been gaining market share in recent years. Some electricity-based heating systems were therefore also included as a reference. Due to the high energetic performance of heat pumps only small CO₂ reductions can be obtained by replacing heat pumps with wood-based heating systems. The largest CO₂ reduction that can be obtained is 55 tons CO₂/TJ by a large-scale CHP. On the other hand very large CO₂ reductions can be obtained by replacing resistance heating. Up to 160 tons CO₂/TJ can be achieved for a wood-fired boiler instead of resistance heating. These high CO₂ reductions come from the avoided CO₂ emissions of electricity generation.

3.3. CO₂ reduction per GWh of electricity

From the analysis in Section 3.2 it can be concluded that valorization of wood waste in coal-fired plants or large-scale CHP has the largest CO₂ reduction potential with a CO₂ reduction that is larger than 70 tons CO₂/TJ for heating oil as well as for natural gas as a reference fuel in heating systems. The high efficiency of CHP is responsible for its high CO₂ reduction whereas for co-combustion in coal plants the high CO₂ emission factor of the substituted coal is responsible for the high CO₂ reduction. Technical constraints limit however the percentage of wood waste that can be co-fired in a coal plant. Presently, in Belgian coal-fired plants a maximum of 10% wood waste is co-fired (Theunis et al., 2003). At these low co-firing rates a coal plant will still have much higher emissions per GWh electricity than CHP as can be seen from Fig. 3. The emissions of CHP are 402 tons CO₂/GWh lower than the NGCC reference while the emissions of a coal plant will be reduced by only 83 tons CO₂/GWh when co-firing 10% of wood waste. Moreover the CO₂ reduction of co-firing wood waste is much smaller than the CO₂ reduction of 432 tons CO₂/GWh corresponding to a shift from coal- to gas-based electricity generation. Even at a co-firing rate of 40%, which is expected to be possible in the future (R. van Ree et al., 2000), the CO₂ reduction is with 332 tons CO₂/GWh lower than the CO₂ reduction from a shift from coal- to gas-based electricity. A co-firing rate of at least 52% is required to have the same CO₂ reduction per GWh electricity as a shift from coal- to gas-based electricity. At this co-firing rate the CO₂ emissions of a coal plant

are still 15 times higher than the CO₂ emissions of CHP. It is clear that, even at moderate operational CHP efficiencies, electricity generated from CHP leads to much lower CO₂ emissions than electricity from a coal plant equipped with co-firing of wood waste.

3.4. The effect of co-firing wood waste on the marginal costs of electricity plants

Fig. 3 clearly illustrates that a shift from coal- to gas-based electricity can decrease CO₂ emissions more than co-firing of 10 or even 40% of wood waste in coal plants. Such a shift is currently supported by the EU ETS. Although a decreased use of coal for electricity generation is absolutely necessary from the point of view of CO₂ emissions, other considerations will ensure that a certain fraction of the total electricity generation will remain coal-based. Diversification of the electricity generation system is for instance absolutely essential for price stability and security of supply. In the transition period before the introduction of CO₂ sequestration technologies, other emission reduction techniques, like co-firing wood waste, can be applied to reduce the CO₂ emissions of coal-based electricity generation. Excessive support for coal-based electricity should, however, be avoided as it could counter the effect of the EU ETS. In the light of this concern the effect of the current support for co-firing wood waste via tradable GC on the marginal costs of coal- and gas-based electricity plants is studied.

Fig. 4 shows that the marginal cost of a coal plant with 10% co-firing of wood waste and without support from GC is only slightly higher than without co-firing. Conversely co-firing of wood waste in a gas-based plant without GC will reduce the marginal cost to a small extent. As a result the difference in marginal costs of coal and gas plants would decrease by co-firing wood waste in the absence of GC from 3.8 €/GJ_e to 3.2 €/GJ_e. Besides a CO₂ reduction by direct substitution of fossil fuels by wood waste, also a CO₂ reduction from a small shift from coal- to gas-based electricity could occur due to a lower difference in marginal costs. With GC the difference in marginal costs decreases further but only slightly to 3.0 €/GJ_e. However due to the fact that BIGCC is not yet commercially available the difference in marginal costs increases with 56% in the presence of GC to 5.9 €/GJ_e which is very close to the difference in marginal costs of 6.2 €/GJ_e in the absence of EU ETS (Section 3.1). It can be concluded that, as long as NGCC plants are not adapted to BIGCC, the actual support for co-firing wood waste via GC effectively counterbalances the effect of EU ETS.

Given these boundary conditions the consistent trend in the last two decades to switch from coal- to gas-based electricity in Belgium may come to an end (Eurostat, 2009). In the worst case the trend may even be reversed. In the period 1991–2006 the fraction of coal-based electricity has decreased from 23% to 8% and the fraction of gas-based

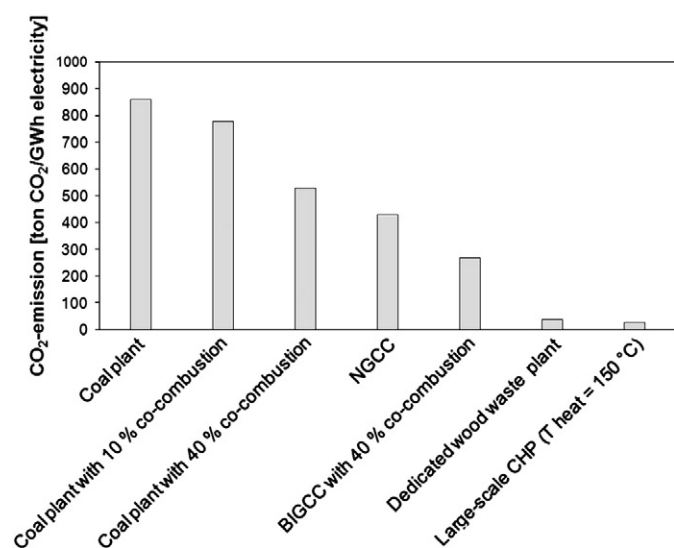


Fig. 3. CO₂ emissions (in ton CO₂/GWh electricity) corresponding to different options for electricity generation.

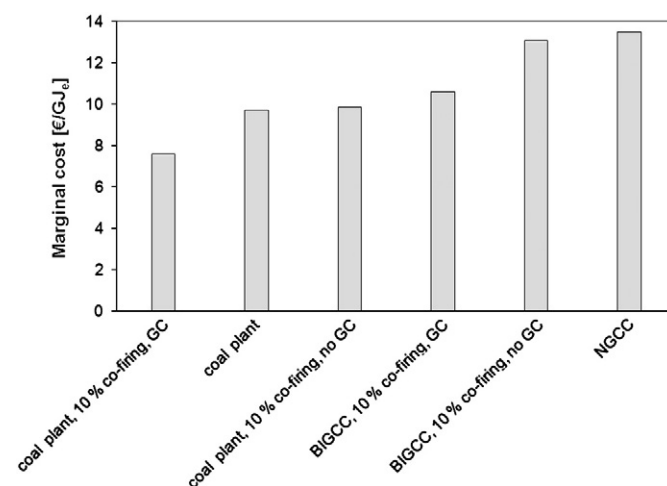


Fig. 4. The effect of co-firing and GC on the marginal costs of electricity plants.

electricity has increased from 12% to 30% (Eurostat, 2009). The total fraction of electricity from coal and gas plants can be considered constant as it increased only slightly from 35 to 38% in the same period. Therefore Eq. (6) can be used to estimate the shift from gas-based to coal-based electricity which would compensate entirely for the CO₂ reduction by co-firing wood waste in coal plants. With 10% co-combustion an increase in the fraction of coal-based electricity in the total electricity generation from coal- and gas-fired plants of 24% from 21% to 26% or from 8% to 10% of the total electricity generation from all plants would be enough to compensate for the CO₂ reduction of co-firing. This can be achieved without extending coal-based capacity. In 2006 6848 GWh electricity was generated with 2142 MW of coal plants (Delarue and D'Haeseleer, 2007; Eurostat, 2009). This means that these coal plants operated on average 3197 h per year at full load or had an average load level of 36.5%. An increase in the fraction of coal-based electricity from 8 to 10% would correspond to an increase of the average load level to 45.6% or 3996 h per year at full load. The reduced marginal cost due to government support of coal plants with co-firing of wood waste could in the long-term lead to an increase in the installed capacity of coal plants thereby substituting gas-based electricity with much higher marginal costs and much lower CO₂ emissions. These long-term effects can, however, only be evaluated correctly if investment costs and fuel availability are also taken into account, which was not the aim of this study.

4. Conclusion

In this paper the CO₂ reduction for different options for energetic valorization of wood waste was calculated. The results show that valorization in large-scale CHP or co-firing in coal plants has the largest CO₂ reduction per TJ wood waste, for both gas- and oil-based reference heating systems. The CO₂ reduction of valorization in a small-scale CHP or a wood-based boiler is also high, but only if an oil-based heating system is replaced. Valorization in a BIGCC or a dedicated wood waste electricity plant results in a CO₂ reduction which is almost one third lower and less than half the CO₂ reduction of co-firing in coal plants respectively. Due to the high efficiencies of heat pumps only small CO₂ reductions can be obtained by replacing heat pumps with wood-based heating systems. On the other hand very large CO₂ reductions can be achieved by replacing electric resistance heating.

The high efficiency of CHP is responsible for its high CO₂ reduction per TJ wood waste whereas for co-combustion in coal plants the high CO₂ emission factor of the substituted coal is responsible for the high CO₂ reduction. However, at current co-firing rates of 10% the CO₂ reduction per GWh of electricity that can be achieved by co-firing in coal plants is five times lower than the CO₂ reduction per GWh of large-scale CHP. As a result large-scale CHP is the only technology that can combine a high CO₂ reduction per TJ wood waste with a high CO₂ reduction per GWh electricity. Moreover a shift from coal- to gas-based electricity would yield a CO₂ reduction per GWh, which is even more than five times the CO₂ reduction of co-firing wood waste in coal plants. Even at co-firing rates of 40% the CO₂ reduction per GWh remains lower than the CO₂ reduction of CHP or a shift from coal- to gas-based electricity.

A shift from coal- to gas-based electricity generation is currently supported by EU ETS. Analysis of the effect of government support (by GC) for co-firing of wood waste in electricity generation plants on the marginal costs of electricity plants revealed, however, that the effect of EU ETS is effectively counterbalanced due to the fact that BIGCC is not yet commercially available. Whereas EU ETS stimulates the use of less carbon intensive fuels (like natural gas) over the use of carbon intensive fuels (like coal), the GC system promotes the use of renewable energy sources (such as uncontaminated wood waste). Since co-firing of wood waste in gas-fired power plants is not yet a commercial option, the GC system directs the wood waste towards coal-fired power plants. This could lead to an increase in coal-based

electricity generation with a corresponding increase in the average CO₂ emission factor of the Belgian electricity generation system as a result thereby counteracting the effect of EU ETS. An increase of the fraction of coal-based electricity in the total electricity generation system from 8 to 10% at the expense of the fraction of gas-based electricity due to the government support for co-firing wood waste would compensate entirely for the CO₂ reduction by substitution of coal by wood waste. This increase can be achieved merely by raising the average load level of existing coal-based electricity generation plants. This clearly illustrates the risk of a 'rebound' effect on the CO₂ reduction due to government support for co-combustion of wood waste in an electricity generation system with large installed capacity of coal and gas-fired plants.

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